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Building energy research in Hong Kong: A review

Zhenjun Ma, Shengwei Wang *

Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

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ABSTRACT

Hong Kong is located in a typical subtropical region. The buildings in Hong Kong are subjected to high cooling demands for their air-conditioning systems throughout most of the year, and their contribution toward the total energy consumption is about 40%. Therefore, energy efficiency in buildings is essential to reduce the global energy use and improve the local environmental sustainability. This paper provides an overall review of the building energy research and efforts in Hong Kong over the last decade. Various aspects and energy saving measures, including energy policy, energy audit, design, control, diagnosis, building performance evaluation and renewable energy systems, studied or used to enhance the energy efficiency in buildings are reviewed. A brief introduction of the Hong Kong Building Energy Codes (BEC) and Hong Kong Building Environmental Assessment Method (HK-BEAM) are also provided to present the efforts of the local government and community on energy efficiency in buildings. This review aims at providing building researchers and practitioners a better understanding of buildings energy saving opportunities and approaches in cities particularly in subtropical regions and taking further proper actions to promote buildings energy efficiency and conservation.

Contents

* Corresponding author. Tel.: +852 2766 5858; fax: +852 2774 6146.
E-mail address: beswwang@polyu.edu.hk (S. Wang).

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1. Introduction

Hong Kong is located in a typical subtropical region and is one of the most densely populated developed cities in the world. The climate in Hong Kong tends towards temperate for nearly half of the year and the buildings in Hong Kong are subjected to high cooling demands throughout most of the year, especially during hot and humid summer months. Due to the rapid increase in the living standard, the number of air-conditioned buildings and the amount of energy use in these buildings have increased dramatically over the last 10 years. Energy is therefore becoming one of the major issues of concern to the local government and society.

According to the statistics provided by the Hong Kong Census and Statistics Department, the total electricity consumption in past 2007 in Hong Kong was 44888.33 GWh, responsible for about 50% of the total energy end-use, of which 22.5% for the domestic sector and 60.1% for the commercial sector with the remaining used in the industrial sector (8.1%), street lighting (0.24%) and others (9.06%) [1]. The annual electricity consumption profiles of the domestic, commercial and industrial sectors over the past 38 years from 1970 to 2007 in Hong Kong are illustrated in Fig. 1 to present more details [1]. It is showed that the electricity consumption of commercial and domestic sectors was increased dramatically with an average rate of the increase of around 7.80% and 6.67% per year, respectively. However, the electricity consumption of the industrial sector was increased from 1970 to 1989 while it was then decreased gradually since 1989 due to the transition of Hong Kong from an industrial-oriented region to a service-oriented one. Therefore, the domestic and commercial sectors are major energy consumers in Hong Kong and growing trend of energy use in both sectors could be continuously experienced in the future due to the climate changes and economic developments.

In order to achieve energy conservation, help alleviate global warming and improve local environmental sustainability, the Hong Kong Government has paid great efforts on promoting energy efficiency in buildings. In 1991, an Energy Efficiency Advisory Committee was set up to advise the government to take appropriate energy efficiency policies to achieve energy conservation, which was transformed into the Energy Advisory Committee in 1996. In 1994, an Energy Efficiency Office (EEO) was set up under the Electrical and Mechanical Services Department (EMSD) to spearhead and coordinate the government's efforts to enhance energy efficiency and conservation. The EEO has worked extensively to issue codes of practice, such as Building Energy Codes (BECs), and establish related energy efficient guidelines. In 1996, an Energy Efficiency and Conservation Sub-committee was established under the Energy Advisory Committee to consider proposals to promote energy efficiency and conservation in Hong Kong and advice the government on energy conservation initiatives. In 2006, the government launched the ''Action Blue Sky'' campaign to mobilize the community to take proper action at personal level to help improve environmental quality, including adopting energy saving measures. To further improve energy efficiency in buildings, a proposal to introduce mandatory implementation of the BECs for certain new and existing buildings was put forward for public consultation in December 2007. These government efforts have resulted in a comprehensive set of energy efficient programmes/schemes [2–4], and codes of practice [5–10] developed and issued to control the total energy consumption in buildings and help raise the public awareness on the importance of energy saving in buildings. Besides these government efforts, the local building professionals have also devoted considerable efforts on developing and investigating proper energy saving measures and providing good practices to achieve energy conservation in buildings.

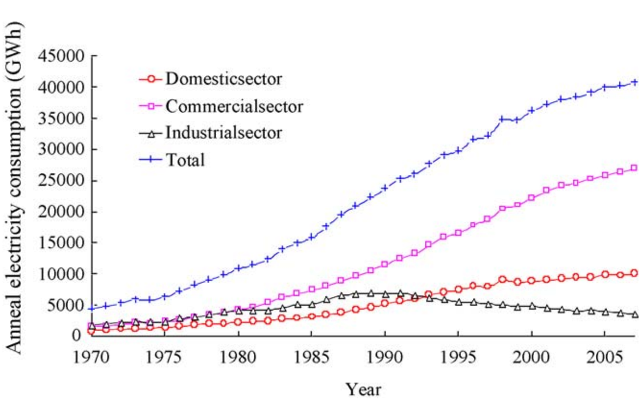

Fig. 1. Annual electricity consumption in domestic, commercial and industrial sectors in Hong Kong from 1970 to 2007 [1].

However, building energy efficiency was not concerned seriously by the private sectors in the past. This situation has changed significantly over the last few years. The developers, building owners and operators in Hong Kong have paid much more attention and efforts in improving building energy efficiency particularly since the last 5 years due to the pressure and benefits on/from reducing the running costs of buildings and awareness on environmental protection.

Buildings consume energy throughout their whole lifecycles, and many aspects and stages of building development and utilization impact their energy and environmental performance, from planning, design, construction and installation to test, commissioning, operation and maintenance. This paper aims at providing a comprehensive review on building energy research in Hong Kong to present the state of the art. Major studies associated with the energy saving and energy use in buildings published during the last decade were reviewed according to the different methods/approaches used. The Hong Kong Building Energy Codes (BECs) and Hong Kong Building Environmental Assessment Method (HK-BEAM) are also briefly introduced to present the government and community efforts. The review was carried out based on the different technologies used to promote energy efficiency in buildings.

2. Hong Kong Building Energy Codes and related studies

2.1. Overview of Hong Kong Building Energy Codes

Building Energy Codes (BECs) are instruments that guide and specify the direction for improving energy efficiency practices [11]. To prompt energy conservation in buildings, the Hong Kong Government has issued a total of six BECs that address energy efficiency design of buildings [5–10]. Fig. 2 is a framework of these comprehensive BECs, in which all codes of practice were categorized into two types: the prescriptive approach and performance-based approach [12]. The prescriptive approach addresses energy efficiency requirements by setting out minimum design requirements. This type of codes is often simple and easy to implement. However, their effects on building energy conservation are indirect since none of them review the building as a whole [13]. The prescriptive codes developed in Hong Kong cover all building related aspects, such as lighting installation, air conditioning installation, electrical installation, lift and escalator installation and building envelope. Among these five codes, the code of practice for overall thermal transfer value (OTTV) in buildings [5] was developed by the Buildings Department and enforced in 1995 under Building (Energy Efficiency) Regulation [4], aimed at reducing external heat gains through the building envelope and, therefore, achieving energy saving in

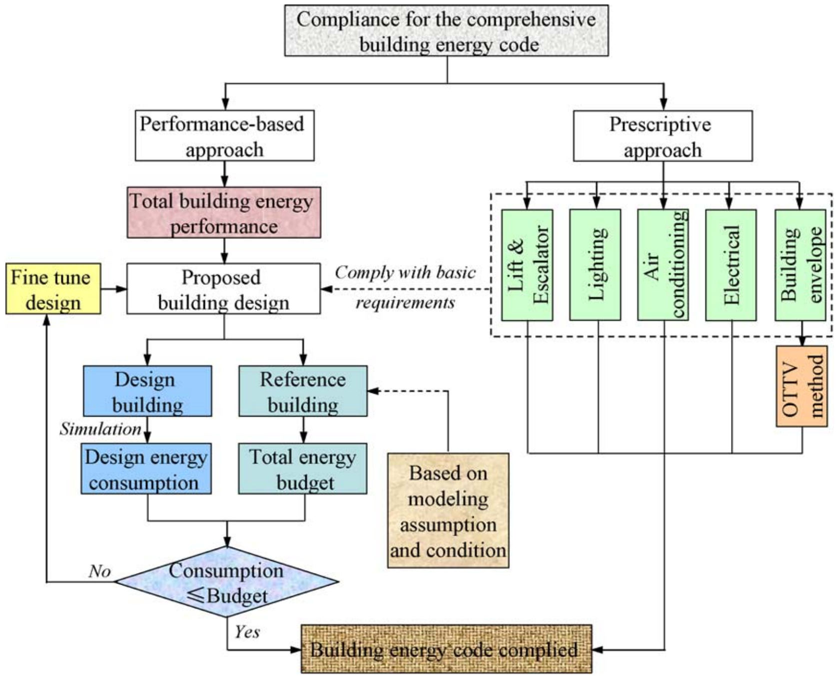

Fig. 2. Framework of the comprehensive building energy codes in Hong Kong [12].

buildings. This code is mandatorily implemented for new commercial and hotel buildings in Hong Kong. The other four prescriptive codes concerning building services installations were developed by the EMSD from 1998 to 2000. These codes are implemented on a voluntary basis under the Hong Kong Energy Efficiency Registration Scheme for Buildings (HKEERSB) [2]. The HKEERSB was launched in 1998 in order to promote the adoption of the BECs by providing the certification to a building complying with one or more of the BECs.

Compared with the prescriptive approach, the performance-based approach emphasizes on the total energy consumption of buildings and allows a certain trade-offs among the system components. Therefore, it deals with the building in a systematic and holistic manner and provides rooms for innovative design. However, this type of codes is generally complicated and the implementation of them often requires extensive work and skills. In Hong Kong, the performance-based building energy code was launched in 2003 by the EMSD under the HKEERSB and is implemented on a voluntary basis.

To better reflect good design practices and the advance in energy saving technologies, the OTTV code was further updated in 2000, while other five codes were updated in 2005 and 2007, respectively. According to the statistics provided by the EEO, up to Oct. 2008, 2206 registration certificates were issued to 915 building venues involving 2397 installations that comply with the BECs [2].

2.2. Overview of studies on Building Energy Codes

Aiming at providing good knowledge and useful information for further development and enhancement of BECs, a number of local researchers have studied and investigated the characteristics of BECs and the factors that affect their developments and applications. A review of early building energy standards in Hong Kong was provided by Lam and Hui in 1996 [13]. The obstacles and barriers in delivering energy efficiency to the marketplace were also discussed in this study. Hui [14] investigated building energy efficiency standards in Hong Kong and mainland China. The requirements of specific energy efficiency laws and codes for buildings were briefly reviewed and how these requirements affecting building designs were discussed. Chan and Yeung [15] evaluated the BECs in Hong Kong and their improvements on local environment by considering the energy savings, environment impacts and cost. The potential reduction of greenhouse gases emission to the environment was predicted in order to estimate the usefulness of the BECs. The results showed that the application of the BECs on commercial buildings can result in reduced energy consumption and a reduction of greenhouse gas emission can also be observed. To enhance the BEC application and achieve notable improvements in building energy conservation, a development report titled 'Study on Enhanced Promotion of Building Energy Codes in Hong Kong' was prepared by Hui [16] in 2007 for the EEO. By studying the worldwide experience and local context, the key issues and effective strategies for the implementation of the BECs in Hong Kong were identified.

As presented early, the OTTV code is the only code that is mandatorily implemented in Hong Kong and the calculation of OTTV is therefore becoming a prerequisite requirement in the submission of building plans for approval. During the past decade, the local researchers have paid great efforts on examining the appropriateness and limitations of using OTTV as a building envelope energy performance index in regulatory control [17–19], and on the modification of the OTTV equations by using appropriate approaches based on the local climate conditions [20,21], as well as on the investigation of the interactions of the OTTV with other major design considerations and their implications for energy efficiency in buildings [22,23]. The efforts were also paid on studying the effects of building envelope designs adopting the OTTV code on the building energy use and cooling load requirements [24–27]. It is noted that a relatively comprehensive overview of the research studies on the OTTV code in Hong Kong before 2005 can be found in Ref. [18].

These research studies related to the application of BECs in Hong Kong are useful for building envelope designs and legislative control of energy use in buildings. The results obtained from these studies will be useful for the government to evaluate the current existing BECs, and further to update these BECs to make them more suitable for local conditions.

3. Hong Kong Building Environmental Assessment Method

The Hong Kong Building Environmental Assessment Method (HK-BEAM) is a significant private sector initiative in Hong Kong, with an aim to promote environmentally friendly design, construction, commissioning, management and operation as well as maintenance practices for buildings [28]. Since the building energy performance is one of key factors in the evaluation process and it contributes a significant portion to the overall assessment results, HK-BEAM is therefore introduced in the following briefly.

3.1. A brief introduction of HK-BEAM

HK-BEAM was initiated by the Real Estate Developers Association of Hong Kong in 1996 largely based on the UK Building Research Establishment Environmental Assessment Method (BREEAM). It is owned by the HK-BEAM Society [29] and operated under the guidance of the HK-BEAM Steering Committee on a voluntary basis. The HK-BEAM Society is a non-profit organization. The mission of the Society is to oversee the on-going development and implementation of HK-BEAM standards for building assessment, performance improvement, certification and labeling. The Department of Building Services Engineering, The Hong Kong Polytechnic University (BSE-PolyU) undertakes technical research and development of the standard in collaboration with different parties, including the Department of Architecture, The University of Hong Kong, and the Business Environment Council, under the direction of the Society Steering Committee [28].

The first two versions of HK-BEAM were for new and existing office buildings launched in 1996 [30,31]. Both versions were further reviewed in 1999 and 2004 by extending the assessment range of building types and addressing the implementation problems experienced previously, which leads to two updates to the previous versions [32,33]. To reduce the environmental impact of new residential buildings by using the best available techniques and within reasonable cost, a new version for new residential buildings was issued in 1999 [34].

In HK-BEAM, over 100 best practice environment criteria on the key aspects of buildings in Hong Kong were defined. These performance criteria cover a wide range of environmental issues related to the impacts of buildings on the environment in the global, local and indoor scales. During an assessment, the environmental performance of the building submitted will be quantified by comparing its environmental performance with the performance criteria defined in HK-BEAM. Credits will be awarded if the defined performance criteria are satisfied. After the assessment, the building will receive a HK-BEAM certificate with a rating of Bronze, Silver, Gold or Platinum according to its performance. It is worthy noticing that when defining the energy performance criteria, HK-BEAM makes reference to the Hong Kong BECs. Fig. 3 illustrates the key features of the building energy performance assessment for new buildings in the latest version of HK-BEAM [32]. The detailed assessment procedures can be found in Ref. [32].

Adopted by over 100 premises, HK-BEAM is becoming one of the most widely used assessments and labeling schemes for buildings in the world on a per capita basis [29].

3.2. Overview of studies on HK-BEAM

Since the efficient use of electricity is one of major parts in the assessment in HK-BEAM, the BSE-PolyU has devoted considerable efforts on this subject during the last decade. The energy performance criteria in HK-BEAM for obtaining the relevant credits were discussed in Ref. [35], while the detailed building energy performance assessment method in HK-BEAM was described in Refs. [35,36]. A conceptual framework for formulating an incentive-

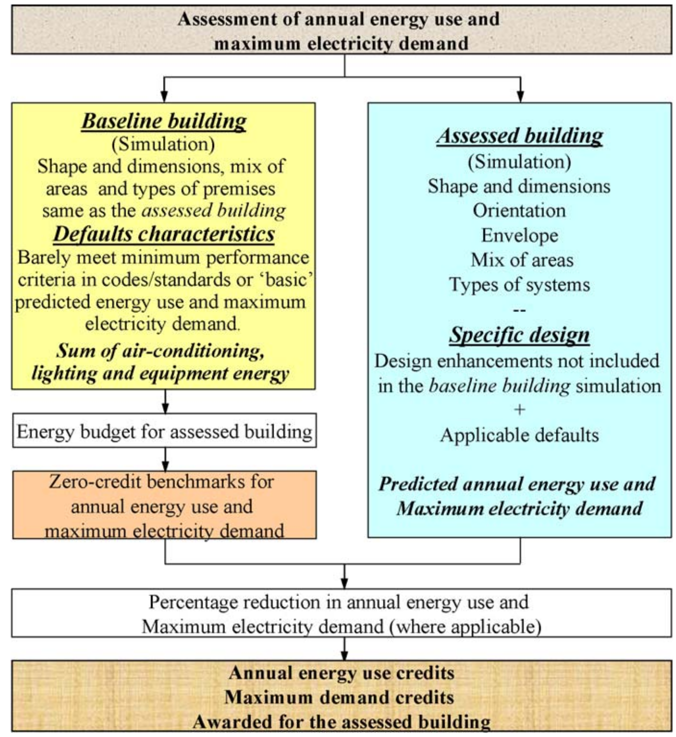

Fig. 3. Building energy performance assessment in HK-BEAM [32].

crediting scale for accrediting criteria within HK-BEAM was proposed in Ref. [37] to encourage greater energy reduction efforts. To help the developers and designers identify the economic impact and cost effectiveness of the accredited criteria, economic benefit–cost ratios for various criteria within HK-BEAM were developed in Ref. [38].

Aiming at simplifying the energy performance assessment in HK-BEAM, multiple linear regression models were developed by Lee et al. [39] for use in the assessment as an alternative to the detailed simulation method. Lee and Yik [40] compared the key assessment criteria in the Hong Kong BECs and the energy performance criteria in HK-BEAM. To investigate how well the energy efficiency of the HK-BEAM certified buildings compared with the buildings in compliance with other assessment schemes, i.e., BREEAM, LEED, and mainland China codes, simulation studies were conducted to benchmark the energy use assessments in these schemes [41,42].

The results obtained from above studies have helped enhance the energy performance criteria and energy performance assessment method within HK-BEAM. These studies have already and will be continuously served as good references for future development and update of the current versions of HK-BEAM.

4. Building energy research on control and diagnosis

Proper control and diagnosis of buildings and building services systems have significant impacts on energy and cost efficiency of buildings besides proper system design and selection and maintenance of individual components.

4.1. Studies on control and optimization

To formulate control and optimization strategies, the first step is to select proper control and optimization method according to the specifications of the targeted application. The major control and optimization methods developed and utilized in the building Heating, Ventilation and Air-Conditioning (HVAC) field have been

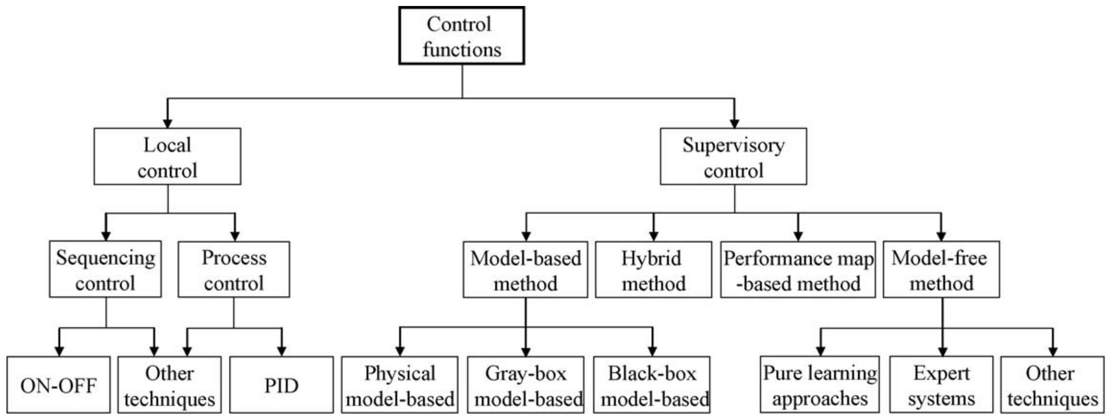

Fig. 4. Classification schematic of control methods in building HVAC systems [43].

categorized by Wang and Ma in a review paper [43]. Fig. 4 is the overall scheme of this categorization, in which whether a method is specified as a model-based method or a model-free method is dependent on whether the numerical models are used. According to this categorization, the control and optimization studies related to the building energy performance in Hong Kong are reviewed in the following by two groups: the studies using supervisory and optimal control and the studies based on local controls. It is worthwhile to notice that supervisory and optimal control refers to the control strategy that is formulated using a systematic approach by considering the system level and subsystem level characteristics and interactions among the overall system.

4.1.1. Studies on supervisory and optimal control

Over the past decade, local building researchers and professionals have paid great efforts on developing and applying supervisory and optimal control strategies for buildings and building HVAC systems to enhance their energy efficiency.

A comprehensive overall review of the state of the art of the research and development as well as application of supervisory and optimal control of building HVAC systems was provided by Wang and Ma [43]. Wang and Jin [44] presented a supervisory control strategy using a systematic approach for VAV air-conditioning systems, in which simplified physical models were utilized to predict the overall system performance and a GA was used to solve the optimization problem of multiple control variables. A novel control strategy for optimizing variable-speed pumps in indirect water-cooled chilling systems was proposed by Wang [45], in which an adaptive and derivative method was used to optimize the speed of seawater pumps by resetting the pressure set-point according to the estimated derivative of the total power of chillers and water pumps with respect to the pressure. To evaluate energy performance and economic feasibilities of different control strategies prior to site implementation, dynamic simulation platforms for buildings and buildings HVAC systems were developed in several studies [46–48]. Simulation exercises based on these simulation platforms showed that energy or cost in buildings can be saved when supervisory and optimal control strategies are used.

Supported by the major local developer, Sun Hung Kai Properties, the research team on Building Automation and Diagnosis led by Prof. Wang in PolyU, has devoted considerable efforts on developing online supervisory and optimal control strategies for complex building HVAC systems for practical and real-time applications. Since 2005, a set of model-based supervisory and optimal control strategies have been developed and implemented. They include control and optimization of complex chilled water systems, cooling water systems and variable speed pumps with different configurations in complex HVAC systems [49–52], and control and abatement of plume from cooling towers [53,54]. A ventilation control strategy for multi-zone VAV air-conditioning systems [55] and a robust building cooling load prediction scheme using a data fusion technique [56] were also developed. These strategies were developed for practical applications, and the requirements and constraints of practical applications were therefore carefully considered during the development of these strategies. To apply these strategies in practice, an implementation platform, as shown in Fig. 5, was also developed [48]. Using this platform, these optimal control strategies are being tested and validated in the new landmark building of 108 stories, International Commerce Centre (ICC), in Hong Kong. The estimated annual energy savings provided by implementing the optimal control strategies together with the revisions on the system configuration and equipment selection are about 6,000,000 kWh.

To optimize the operation of a direct-fired absorption chiller system, a system-based control strategy was developed by Chow et al. [57], in which neural networks were used to model the system characteristics and a genetic algorithm (GA) was used to search for optimal solutions. For the effective energy management of building HVAC systems, a simulation optimization approach was proposed by Fong et al. [58], in which an evolutionary programming was used to handle the discrete, nonlinear and highly constrained optimization problems. The real-time predictive supervisory control of building thermal systems with thermal mass was studied by Chen [59]. The simulation of passive solar floor heating systems with thermal mass showed that about 10–27% of operating cost in the system can be saved by using this strategy. An optimization strategy for water-cooled chiller systems using a systematic approach was presented by Yu and Chan [60], in which a load-based speed control was introduced for the tower fans and condenser water pumps to achieve optimal operational performance.

The above studies have demonstrated that the application of supervisory and optimal control strategies for buildings can result in significant energy or cost savings. However, due to the increased complexities of the programs and control systems, system level parameters need to be identified, which would result in high requirements on the efforts and skills to handle the test and commissioning.

4.1.2. Studies on local controls

In this paper, the control studies that were related to building energy efficiency, but were not formulated using a systematic approach, are classified into this category.

To improve energy efficiency and indoor air quality (IAQ), a robust control strategy using "freezing", gain scheduling, I-term

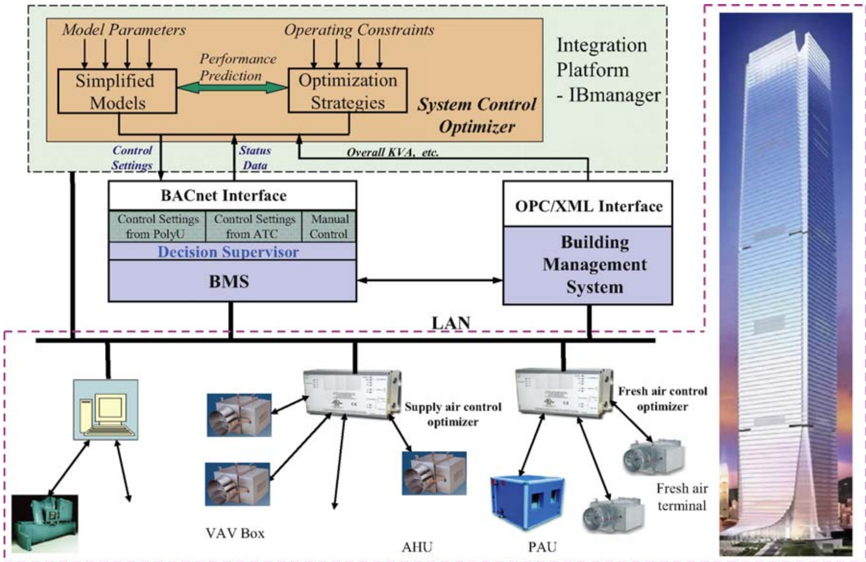

Fig. 5. In situ implementation architectures of online control strategies [48].

reset and feedback transition control, was developed by Wang and Xu [61,62] to handle the control instability occurring when combining demand control ventilation (DCV) strategy with economizer control, and a dual-mode DCV strategy was developed by Chao and Hu [63] to maintain some of the occupant-related and non-occupant-related indoor air pollutants at acceptable levels. A strategy for online resetting of the VAV static pressure set-point was developed by Wang [64] for energy efficiency. To minimize the energy consumption of air-side systems, an adaptive comfort temperature (ACT) module and a new DCV module were developed by Mui et al. [65,66] to reset the indoor comfort temperature. To adapt to the presence of the measurement faults in outdoor air flow rate control and minimize the resulting increase in energy consumption, a fault-tolerant control strategy for outdoor ventilation air flow rate in buildings was developed by Wang and Chen [67] based on neural networks. Chan and Yu have worked extensively on improving energy performance and operating efficiency of air-cooled chillers by optimizing the condensing temperature set-point [68,69]. The optimal load sharing strategy for multiple-chiller systems and the part load performance of air-cooled chillers were also studied for energy efficiency [70,71].

The results obtained from above studies have showed that these control strategies can help improve the system control stability, reduce the building energy consumption and/or enhance IAQ. These studies are useful for building operators to better understand how to improve the building operational performance. In addition, these strategies are the basis and can be used in supervisory and optimal control strategies to ensure the robust operation and keep track of control settings considering the dynamic characteristics of the local process environment.

4.2. Studies on Fault Detection and Diagnosis (FDD)

Fault Detection and Diagnosis (FDD) applications play significant roles in process engineering. The main benefits of using FDD in buildings and HVAC&R systems derive from reduced energy consumption and/or operating costs and improved IAQ. In Hong Kong, the research team on Building Automation and Diagnosis led by Prof. Wang in BSE-PolyU, is an active research group and has been working extensively on the FDD applications in building HVAC systems since the late 1990 to help improve the operating efficiency of buildings. It is reflected by the fact that a number of robust FDD schemes for various building HVAC components have been developed.

A sensor fault detection and diagnosis tool for air handling units (AHUs) using principal component analysis (PCA) method was proposed by Wang and Xiao [72–75]. In these studies, two PCA models were built based on the heat balance and pressure-flow balance of the air-handling process to reduce the effects of the system non-linearity and to enhance the robustness of the strategy in different control modes. Sensor faults were detected using the Q-statistic or squared prediction error (SPE) and isolated using the SPE and Q-contribution plot supplemented by a few simple expert rules. The PCA models were updated using a condition-based adaptive scheme to follow the normal shifts in the process due to the change of working conditions. Rules were built to determine the time when the PCA models need to be updated. The results from simulations and field tests showed that these strategies are robust in detecting/diagnosing sensor faults in the AHU component. To overcome the inefficiency of PCA in isolating faults due to its pure data-driven nature, an expert-based multivariate decoupling method was proposed by Xiao et al. [76] to enhance the capability of the PCA-based method in fault diagnosis. A FDD strategy for monitoring and diagnosing the degradation in the performance of heating/cooling coil valves was developed by Wang and Jiang [77], in which a recurrent cerebellar model articulation controller (RCMAC) was used to learn the normal characteristics of the valve and two characteristic variables were defined as the degradation index and the waveform index for analyzing the residual errors.

To improve energy and control performances, Wang and Qin [78] developed a strategy for the flow sensor fault detection and validation of VAV terminals in air-conditioning systems using the PCA method. The sensor faults were detected using both the T^2 statistic and SPE and isolated using the SPE contribution plot. The faulty sensor was reconstructed after it was isolated, and the FDD strategy repeated using the recovered measurements until no further fault can be detected. Qin and Wang [79] presented the results of a site survey study on the faults in VAV terminals and developed an automatic FDD strategy for VAV air-conditioning systems using a hybrid approach. This hybrid approach utilized expert rules, performance indices and statistical process control models to detect and diagnosis the faults occurring in the system.

The robust sensor fault diagnosis, validation and/or reconstruction in building central chilling systems were also studied by

Wang and his collaborators. The sensor FDD strategies in early studies were developed based on the fundamental of mass, heat and energy conservation relations [80–82]. These strategies evaluated soft sensor faults (biases) by examining and minimizing the sum of the squares of concerned mass and steady state energy balance residuals represented by the corrected measurement over a period. Consequently, sensor FDD strategies were developed based on the PCA method or improved PCA method by combining with other method, i.e., wavelet analysis [83–85]. To detect and diagnosis the component faults in centrifugal chillers, Cui and Wang [86] developed a model-based online adaptive FDD strategy. This strategy was developed based on six selected physical performance indices. A set of rules for faults and their impacts on the six performance indices were deduced from theoretical analysis, and then served as the fault classifier. An online adaptive scheme was used to estimate and update the thresholds for detecting abnormal performance indices by analyzing uncertainty coming from both model-fitting errors and measurement errors. To detect and diagnosis component faults and sensor faults in centrifugal chillers simultaneously, Wang and Cui further [87] further developed a robust FDD strategy that consists of a model-based chiller FDD scheme and a sensor FDD&E scheme, as shown in Fig. 6. The sensor FDD&E scheme used a PCA-based method to capture the correlations among the major measured variables in centrifugal chillers. The chiller FDD scheme was developed based on six physical performance indices. The robustness of this strategy was validated using the laboratory data from ASHRAE RP-1043 and field data from a centrifugal chiller in a real building in Hong Kong.

For the FDD of building HVAC systems, several publications by other researchers in Hong Kong are also available in the literature. With the combination of the strengths of fuzzy reasoning and global optimization of GAs, an intelligent technique based on fuzzy-genetic algorithm (FGA) for automatically detecting faults in HVAC system was developed by Lo et al. [88]. In the meantime, a model-based FDD strategy for HVAC systems was developed by Liang and Du [89] using Support Vector Machine (SVM) method.

These studies have demonstrated that robust FDD strategies for building HVAC systems can help identify sensor faults and component faults occurring in HVAC systems reliably, and further help the systems put back into normal operation. This will in turn help achieve better IAQ for occupants and lower building energy consumption. The outcomes from these studies can also provide effective prototypes for developing robust FDD strategies that can be readily implemented and applied in practice.

5. Building energy research on advanced design

Building design is the process of providing all information necessary for construction of a building that will meet its owner's requirements and also satisfy public health, welfare and safety requirements [90]. In this paper, the advanced design refers to the studies that focused on developing new HVAC systems or using alternative design options to enhance energy performance of building services systems. To reduce the energy consumption in buildings, a number of studies related to the building energy efficient design have been proposed by local professionals.

An HVAC system combining chilled-ceiling with desiccant cooling was proposed by JL Niu et al. [91] for hot and humid climates where air dehumidification is required to maintain the indoor air humidity within a comfort zone and to reduce the risk of water condensation on chilled panels. The simulation results showed that this new system could save up to 44% of primary energy consumption as compared with a conventional constant volume all-air system. A low energy air-conditioning system that combines the cooled ceiling, microencapsulated phase change material (MPCM) slurry storage and evaporative cooling technologies was proposed by Wang et al. [92]. The major feature of the system was that the thermal energy storage using MPCM slurry enables the evaporative cooling to be stored in MPCM slurry at 24-h operation mode whenever the wet-bulb temperature reached the predetermined set-point.

An alternative design configuration for the secondary chilled water system in a super high-rise commercial building in Hong Kong was proposed by Ma et al. [93]. The preliminary energy performance evaluation results showed that this alternative design configuration can save a significant amount of pump energy as compared with the original design configuration. The new designs

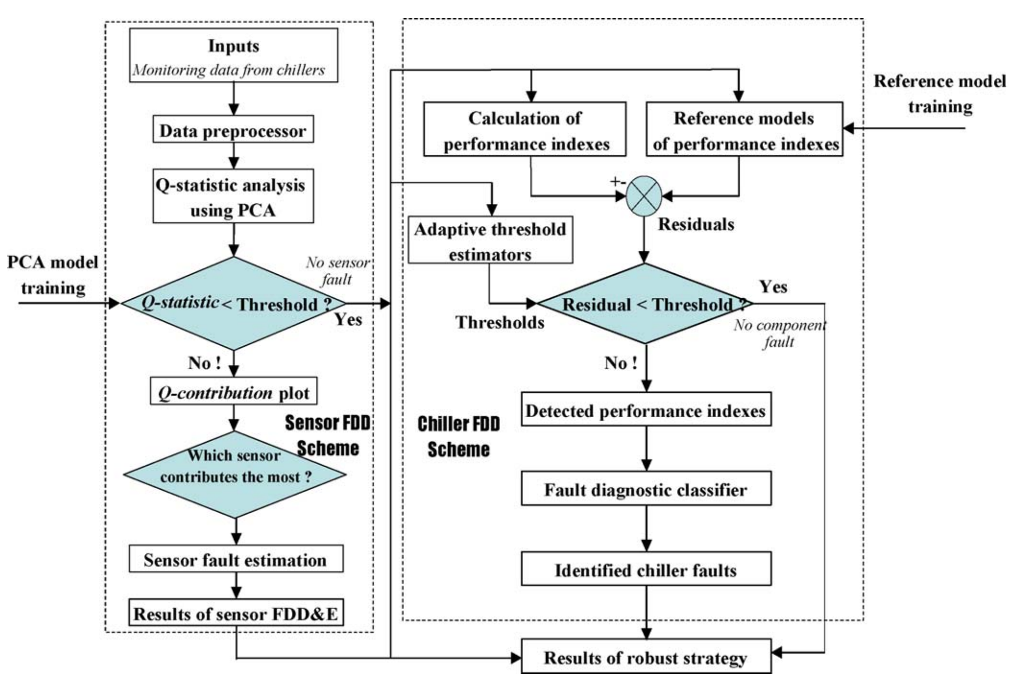

Fig. 6. Flow chart of the robust chiller FDD strategy [87].

for chilled water circuit were proposed by Yik [94]. These new designs only require minor extra provisions, including the installation of supplementary pipes and fittings and a few additional control devices, and allow the full and part load performance of chillers to be measured conveniently and expeditiously. The low energy design of air-cooled chillers in HVAC systems was studied by Yu and Chan [95,96]. The economic benefits using different design options with respect to the number and size of chillers were studied.

To optimize the design of district-cooling systems (DCS), which are the mass scale production of the chilled water that is delivered to serve a group of buildings, a GA was used by Chow et al. [97] to search for the desirable mix of building types to be served by the DCS, and a GA incorporated with local search techniques was used to find the optimal/near optimal configuration of the piping network in DCSs [98]. A simple building design method that allows a quick determining the amount of thermal mass, the total surface area and the thickness of thermal mass was proposed by Li and Xu [99], in which three design-related parameters, i.e., the time constant of the system, the dimensionless convective heat transfer number and the Fourier time constant, were considered.

Design weather data play significant roles in the design of buildings and size of building services systems. Improper design weather data may cause systems/components to be oversized or undersized, which will result in unnecessary extra capital investment and low part load efficiency, and even insufficient cooling/heating energy provided, etc. The importance, properties and proper selection of outdoor design conditions for HVAC designs were discussed by Lam and Hui [100]. The rational selection of near-extreme coincident weather data, including dry-bulb and wet-bulb temperatures and/or solar irradiation for risk-based air-conditioning design was studied by Chen et al. [101,102]. To reduce the equipment oversize problem, Lee et al. [103] established a set of realistic design criteria for lighting power density, occupation density, and appliances' load-intensity for various types of premises.

These design strategies could provide good practices for building designers to adopt advanced design philosophies during the building planning and design stages. The studies on design weather data are also useful for proper designing buildings and sizing building services systems.

6. Building energy research on energy audits/analysis

The energy audit or analysis is a program carried out to understand the energy performance of buildings. The objectives of an energy audit or analysis are to identify and develop modifications to reduce energy use and/or cost of operating a building [104]. According to the statements provided in Chapter 35 of the ASHRAE Handbook of HVAC Applications, energy audits or analysis can be classified into three levels based on the scope and complexity of work covered, including walk-through assessment (Level 1), energy survey and analysis (Level 2) and detailed analysis of capital-intensive-modifications (Level 3).

In Hong Kong, considerable research work has been carried out based on energy audits/analysis to better understand energy use and energy use characteristics in buildings, and further to propose proper energy efficient measures to reduce energy consumption in buildings. The process of an energy audit and how to formulate an energy audit programme were presented in an early study by Wong and Lee [105]. To help guide the direction of energy auditing and improve the consistency of the energy audit, WK Chow et al. [106] investigated the building energy performance in a tertiary educational institute in Hong Kong by calculating major energy indices, i.e., a building energy index, electric load factors and occupancy load factors.

Based on the analysis of the data collected from building energy audits, Yu and Chow [107] investigated a total of 20 energy saving measures for possible use in local commercial buildings, which aimed at providing useful information for engineers in designing energy efficient commercial buildings. The energy performance in 19 government offices in Hong Kong was studied by Li [108]. The characteristics of government offices, difficulties and results in assessing their building energy performance were discussed and reported. Energy saving opportunities for government offices were identified and proposed based on an energy audit.

Based on the energy audit on a central air-conditioning plant in Hong Kong, Yik and Burnett [109] found that data available from the operation records were insufficient for detailed assessment of equipment efficiency. How the plant performance can be estimated based on the limited data available was discussed. The energy end-use and building characteristics surveys in high-rise residential buildings in Hong Kong were conducted by Wan and Yik [110]. The statistics showed that the electricity use dominated the energy use in public and private residential buildings while the electricity consumption patterns of residential units would be significantly affected by the seasonal utilization of air-conditioners and electric water-heaters.

An early energy audit and site survey by Lam and Chan [111] showed that, in sub-tropical climates, the HVAC system was the largest electricity consumer accounting for 40–60% of the total electricity consumption in buildings, while lighting accounted for 20–30%. The further in-depth energy audits on energy use of residential, office and commercial buildings in Hong Kong were carried out in several studies [112–115]. The results showed that HVAC was the single largest electricity end-user in these three building sectors while electric lighting was the second large electricity consumer in both office and commercial sectors.

A survey of a total of 120 commercial buildings in Hong Kong was carried out by Lam [116]. It was found that the degree of shading at the local peak design condition ranges from 25% to 31%. The older and more established districts tend to have slightly higher degrees of shading. The implications for energy efficiency in the design of commercial buildings were discussed. To investigate the climate change and building energy use implications in Hong Kong, Lam et al. [117] analyzed a total of 40 years (1961–2000) of measured hourly ambient temperature data. The results showed that there is an underlying trend of temperature rise in recent years. Such temperature increases tend to occur more frequently during the winter period and mid-season than the summer months. It was also found that the temperature rise in recent years in Hong Kong would have no significant impact on cooling requirements and energy use in buildings.

These research efforts have provided useful information for local building services system designers, operators and owners to understand the characteristics of energy usages in buildings and increase the awareness of potential energy saving opportunities. The results obtained from these studies could be also useful for the local government to develop more energy efficient policies.

7. Building performance evaluation

Building performance evaluation is essential throughout the various stages of building developments and utilizations. Accurate building performance evaluation can help assist in selecting and adopting energy efficient and cost effective measures to achieve energy conservation in buildings. The research efforts in Hong Kong on this subject are reviewed in the following along with a brief overview of the studies on solar irradiation since it plays significant roles in determining the thermal and energy performance of a building and is therefore important to the design and analysis of both active and passive buildings.

7.1. Studies on building energy and thermal performance evaluation

Since buildings are often exposed to outdoor weather conditions and building components, such as walls and roofs, always exhibit certain thermal effects, numerical techniques which account for transient nature of heat transfer in buildings, have been used by local researchers to predict the thermal performance of buildings. A method/procedure for calculating transient thermal load through building walls was proposed by Wang et al. [118–120]. In this method/procedure, the frequency-domain regression (FDR) method was introduced to estimate simple polynomial s-transfer functions from the frequency characteristics, and further calculate the transient heat flow including thermal response factors and conduction transfer function (CTF) coefficient through the polynomial s-transfer functions. Aiming at providing complete CTF coefficients with a unique set of d values, an improvement to the FDR method for calculating CTFs of building walls was presented by Xu et al. [121]. To estimate transient heat transfer through building structures, a simple time domain calculation method was developed by Xu and Wang [122] to derive thermal response factors and CTF coefficients of finite differential models.

Since building cooling loads directly affect the energy consumption of buildings, the accurate building cooling load prediction is essential for building performance evaluation. The cooling energy evaluation and the influence of the thermal insulation position in building envelopes on the space cooling of high-rise residential buildings in Hong Kong were presented by Bojic et al. [123,124]. The cooling load calculations and the climatic effects on cooling load determination in subtropical climate were presented by Mui and Wong [125] and Li et al. [126], respectively. The cooling load reduction by using thermal mass and night ventilation was presented by Yang and Li [127], in which a simple office building model with air-conditioning at daytime and free cooling at night-time was used to quantify the hourly and overall variation of the cooling load of the air-conditioning.

Another important issue related to the building performance evaluation is the building energy model. A building level energy model was developed by Wang and Xu [128,129]. This model was developed based on the combination of the physically described simplified models of building envelopes and a partially data-driven model of the internal mass. Fig. 7 is a schematic of this building energy model. In this model, the building envelops, including external walls and the ceiling/roof were considered in the 3R2C (i.e., three resistances and two capacitances) models and their parameters were identified using a GA method based on frequency response characteristic analysis, while the building internal mass was viewed as a 2R2C model and its parameters were identified using short-term operation data based on a GA estimator. An alternative simplified building model that combines detailed physical models of building envelopes and a thermal network model of building internal mass was developed in Xu and Wang [130]. The detailed physical models of building envelopes were the CTF models and the thermal network model of the internal mass was the 2R2C model. The parameters in this model were also estimated and optimized using a GA estimator. A flat model comprising a living and dining room model and a bedroom model was developed by Wan and Yik [131] for representing typical residential buildings in Hong Kong. A benchmarking model for the energy use of ventilation systems in air-conditioned offices was proposed by Mui et al. [132].

Based on the building energy models, the building energy use can be simulated directly. It is worthy noticing that building energy use can also be simulated using energy simulation programs, such as DOE-2, EnergyPlus, BLAST, etc. For instance, Chow and Fong [27,133] used BLAST to simulate the energy use in various types of buildings in Hong Kong, including single compartments, industrial building, commercial building, etc.

The results obtained from above studies are important to help understand the cooling loads and energy use characteristics in buildings. They are useful for building designers to improve the thermal design of building envelop and proper size of HVAC systems to reduce the overall energy consumption in buildings. They can also be helpful for building operators to use proper control and operation strategies to reduce the global energy consumption in buildings.

7.2. Studies on solar irradiation

A brief review of the solar distribution models was provided by Chow et al. [134]. Since the basic solar irradiance data for the

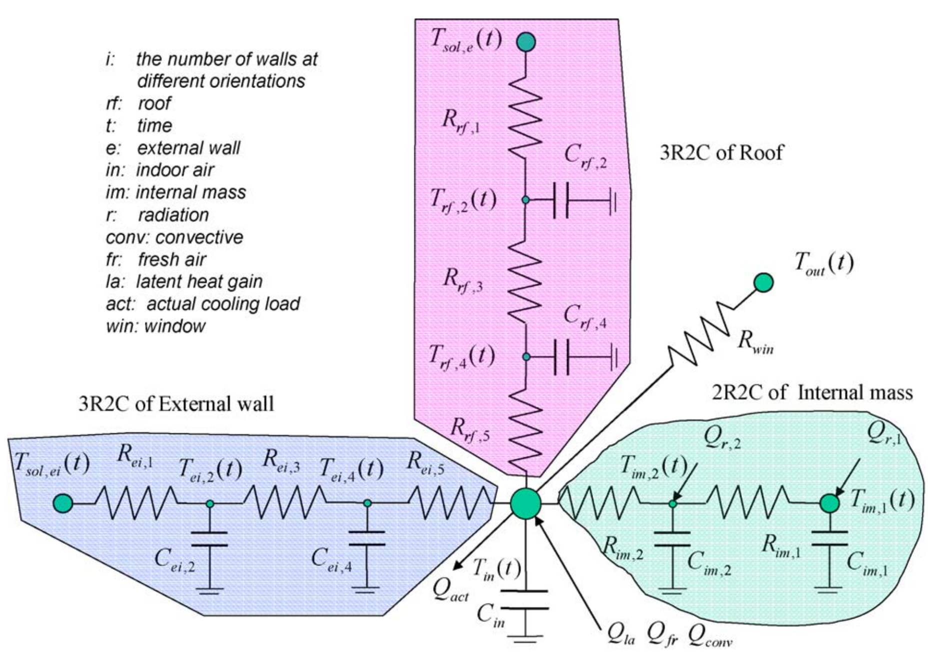

Fig. 7. Schematics of the simplified building energy model [129].

surfaces of interest are not always available, the mathematical models are therefore often developed to predict the solar irradiance on various inclined surfaces using measured horizontal data. An approach to estimate the vertical global irradiance based on direct beam and ground-reflected components was provided by Li et al. [135], while an approach to calculate the solar irradiance on sloped planes by integrating the sky radiance distribution was presented by Li and Lam [136]. An analysis of thermal and solar zone radiation models using an Angstrom–Prescott equation and artificial neural networks was presented by Wan et al. [137]. The performances of two slope irradiance models, namely the Perez point-source model and the Muneer model, and two sky-distribution models, namely the Perez all-weather model and the Kittler standard-sky model, were evaluated by Li and Cheung [138]. The results showed that all four models can accurately predict the solar irradiance of a 22.3° (the latitude angle of Hong Kong) inclined south-oriented surface, indicating the good predictive ability for modeling an inclined surface with a small tilted angle. A solar radiation model using artificial neural networks was developed by Lam et al. [139] for predicting daily global solar radiation using measured sunshine duration. They analyzed the climatic influences on solar modeling as well [140].

The above studies on solar irradiation are crucial to determine the amount of solar heat gain entering a building. They are therefore important for energy efficient building designs for estimating cooling loads and proper sizing of air-conditioning equipment.

8. Building energy research on renewable energy

Renewable energy is the energy that is generated from natural resources, such as wind, solar, rain, tides, geothermal heat, etc. Due to the shortage of energy supply and wide concern on global warming, renewable energy systems have been receiving wide attention and are being recognized as an important and green strategy to generate a sustainable, environmentally friendly and clean energy. When renewable energy systems are integrated into buildings, they can help reduce the peak electrical and cooling demands and, thus, save the total energy consumption of buildings.

In Hong Kong, the government is leading the way on sustainable energy use and has been using renewable energy for over 20 years. A number of researchers in Hong Kong have devoted considerable efforts on renewable energy systems, including solar-based energy systems, ground source-based energy systems and day-lighting schemes.

8.1. Studies on solar-based energy systems

The applications of solar-based energy systems (i.e., photovoltaic system) in buildings have become more widespread. The computer modeling and experimental validation of building-integrated photovoltaic (BIPV) and water heating systems for residential buildings in Hong Kong were extensively studied by Chow et al. [141–144]. The dynamic simulation models for the BIPV and water heating system were developed and used to predict the system dynamic behavior and the long-term performance. The energy performance and payback period of the application of such systems were fully discussed. A comparative study of three different options in applying large-scale BIPV technology in a subtropical hotel building was described by Chow et al. [145]. The results showed that different design options exhibited short-term electrical performance differences, but had similar long-term electricity yields. They also evaluated the performance of a PV ventilated window applying to an office building in Hong Kong [146]. The results showed that a solar cell transmittance in the range of 0.45–0.55 could achieve the best electricity savings.

Aiming at providing the government and community with the information, experience and appropriate legislation to facilitate widespread BIPV applications, a triple strategy, i.e., Technology Assessment, Technology Application and Regulatory Framework, was presented by Close [147] based on a series of research projects undertaken by the PV research group in the University of Hong Kong.

The operational performance and efficiency characteristic of a small PV system was investigated by Li et al. [148]. The performance of the traditional water heating systems (i.e., electric water heaters and towngas water heaters) and two kinds of solar thermal systems (i.e., conventional solar water heater systems and solar-assisted heat pump systems) was evaluated by Li and Yang [149]. The results showed that solar thermal systems have greater economic benefits than traditional water heating systems. The heat transfer across a PV wall was investigated by Yang et al. [150] to determine the cooling load component contributed by BIPV walls. A one-dimensional transient simulation model for the thermal performance of the semi-transparent PV modules was introduced and experimentally verified by Fung and Yang [151]. To obtain the best configurations of the solar assisted air-conditioning system and validate the feasibility of using a liquid desiccant dehumidification system to handle the latent load, the numerical simulation of an open cycle liquid desiccant dehumidification system was studied by Li and Yang [152]. The results showed that energy savings of the liquid desiccant system were impressive as compared to a conventional vapor compression system.

A case study on grid-connected BIPV was presented by Yang et al. [153]. The analysis showed that grid-connected BIPV application was still not economical, but the technology should be promoted due to its huge potential in terms of environmental protection and future development. They also developed a novel model for PV array performance prediction [154]. Five parameters were introduced in this model to account for the complex dependence of the PV module performance upon solar irradiance intensity and PV module temperature. The performance of this model was validated using the field measurement data from an existing BIPV in Hong Kong, and good agreements were observed between the simulated results and the field data. An optimal design of solar water heating system using an evolutionary algorithm was developed by Fong et al. [155]. From the optimization results, it was suggested that the solar collectors can be installed onto the external shading devices as an integrated architectural feature since the optimal tilt angle was 21° and relatively flat.

These studies based on renewable energy systems in buildings have provided prototypes for successful use of solar-based energy systems in buildings for energy efficiency and sustainability.

8.2. Studies on ground source-based energy systems

Although there is limited potential of using ground source heat due to the high density of high-rise buildings in Hong Kong, the use of the ground-source heat pumps in buildings for energy efficiency was investigated and analyzed in several studies. The computer simulation of borehole ground heat exchangers used in geothermal heat pump systems was conducted by Lee and Lam [156]. The simulation of a hybrid ground-coupled heat pump (HGCHP) with domestic hot water (DHW) heating systems using HVACSIM+ was presented by Cui et al. [157]. The results showed that this HGCHP system can effectively alleviate the imbalanced loads of the ground heat exchanger and can offer almost 95% DHW demand. A HGCHP with supplemental heat rejecters for rejecting extra thermal energy when the HGCHP is installed in cooling-dominated buildings was presented by Man et al. [158]. The simulation results showed that the proper HGCHP system can effectively reduce both the initial cost and the operating cost of an air-conditioning system as compared with the traditional GCHP systems.

These studies could provide a basis for further analyzing whether the use of ground source heat pumps is appropriate in the local climate condition.

8.3. Studies on day-lighting

Day-lighting as an important part in a sustainable design has been receiving wide concern. Incorporating day-lighting strategies into building designs is a good practice to reduce the electrical demand and contribute to achieving environmentally sustainable building development [159]. Visual comfort and electric lighting energy issues are two essential criteria to effectively use day-lighting strategies in buildings. The common day-lighting strategies used could include shadings, windows, colors, lighting controls, etc.

In Hong Kong, many efforts have been made on the studying and discussing of the application of day-lighting strategies in buildings for energy efficiency, which are reflected by the fact that several dozens of research papers have been published and can be readily available in the literature. These studies have addressed the study of day-lighting performance and energy implications in buildings by using proper daylight linked lighting controls and/or solar film coating [159–161], the prediction and analysis of daylight illuminance and luminous efficacy [162–164], the investigation of the shading effects from nearby buildings and optimal shading [165,166], the study of the effects of day-lighting on cooling load determination [167], the discussion of optimal daylight design [168,169], etc. A review of the development of day-lighting in schools was provided by Wu and Ng [170]. The potential and problems of using day-lighting in Hong Kong were fully discussed by Chung [171].

The above studies have demonstrated that proper day-lighting schemes cannot only reduce the electric lighting and peak cooling demands in buildings, but also help the air-conditioning systems to be down-sized.

9. Conclusion

This paper presents the state of the art of the building energy studies in Hong Kong. Various research aspects and technologies, i.e., control, design, diagnosis, energy audit, energy analysis, building performance evaluation, renewable energy-based systems, used to promote building energy efficiency and sustainability were reviewed comprehensively. The results showed that all these technologies can provide energy saving opportunities in buildings if they are properly used. The local energy policies and Building Energy Codes as well as Hong Kong Building Environmental Assessment Method (HK-BEAM) were also briefly introduced to address the efforts of local government and community on promoting energy efficiency in buildings.

This review paper could be useful for designers, operators and owners to fully understand energy saving opportunities in buildings and further to take proper energy saving measures to enhance energy efficiency and conservation in buildings. They could help designers adopt proper design options and concepts in the decision making process during the initial planning and design stages and help operators to use advanced control algorithms in practical operations to reduce the global energy consumption in buildings and enhance control stability and environmental sustainability. It could also be useful for the government to evaluate the current building energy policies.

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